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INITIATION OF EXPLOSIVES BY EXPLODING WIRES

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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INITIATION OF EXPLOSIVES BY EXPLODING WIRES

II. Effect of Circuit Resistance on the Initiation of PETN by Exploding Wires

Prepared by:
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ABSTRACT: The effects of circuit resistance and bridgewire length on the initiation of PETN by exploding 1 mil diameter platinum wires were investigated. A one microfarad capacitor charged to 2000 volts was used as the energy source. Increasing circuit resistance reduces the current density and the energy input to the wire lowering the probability of producing detonation in PETN. The importance of keeping the extraneous circuit resistance to an absolute minimum is shown.

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U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

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INITIATION OF EXPLOSIVES BY EXPLODING WIRES
II. Effect of Circuit Resistance on the Initiation of PETN
by Exploding Wires

This report describes preliminary results of a continuing investigation concerning the initiation of explosives by exploding wires. The investigation was performed under Task RUME-4E000/212-1/F008-10-04 Problem No. 019, Analysis of Explosive Initiation.

The results should be of interest to personnel engaged in initiation research and to those interested in the design of exploding bridgewire ordnance systems. The data and conclusions are for information only and are not intended as a basis for action.

The identification of commercial materials implies no criticism or indorsement of these products by the Naval Ordnance Laboratory.

R. E. ODENING
Captain, USN
Commander

C. J. ARONSON
By direction

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INTRODUCTION

1. This is the second report describing experimental results from an investigation on the interaction between an exploding bridgewire and explosive materials, and the factors which affect the process. Previous investigation[1] had shown that for best effecting detonation of PETN by an exploding wire circuit inductance should be kept to a minimum and the bridgewire length of 1 mil diameter platinum wire should be chosen so as to eliminate a definite current dwell period. It was also found that secondary current pulses have little effect on whether or not detonation is produced. This report describes the effect of extraneous circuit resistance on the probability of producing detonation in PETN by exploding platinum wires of various lengths.

2. In order to best effect detonation in an explosive by an exploding wire it is desirable to transfer the highest possible quantity of energy to a volume of explosive in the shortest possible time. It is also obvious that energy will be wasted in any extraneous circuit resistance outside of the bridgewire. This investigation was made to determine the amount of external circuit resistance that could be tolerated and to study the conditions that determine whether or not detonation develops.

ELECTRICAL CIRCUITRY

3. A typical exploding bridgewire circuit employed in ordnance uses a one microfarad capacitor charged to 2000 volts. The actual test circuit used for this investigation has similar parameters and is shown in Figure 1. The transmission line was kept as short as possible consistent with the necessity for testing in an explosive firing chamber. This was done to keep circuit inductance and resistance to a minimum.

4. The circuit differs slightly from the basic circuit described in reference (1). A GL-7964 triggered spark gap is used as the switching device in place of a cold cathode trigger tube. A physically larger capacitor capable of being charged to 5000 volts was also incorporated. The larger physical size of the capacitor results in a slight undesirable increase in circuit inductance. The changes also resulted in a lower circuit resistance.

References are listed on page 10.

TEST PROCEDURE

5. The effect of extraneous circuit resistance on the initiation of PETN by various lengths of exploding platinum wire was determined. An initial series of tests was run using a test circuit having the least possible quantity of extraneous resistance. Extraneous resistance was then intentionally added to the circuit to determine the effect on the initiation of PETN.

6. The experimental methods employed were previously described in reference (1). Briefly, PETN is loaded in a test fixture which permits photographic observation of the growth of explosion from a bridgewire. Current and voltage waveforms are obtained of the exploding wire for each test shot. Concurrently a smear camera record is obtained of the growth of the PETN explosion. The oscillograms and smear camera records are read on a Telereader. The voltage is corrected for the inductive component and the instantaneous resistance, instantaneous power, and cumulative energy values are then calculated.

EXPERIMENTAL RESULTS

7. The first test series was run with the basic circuit (circuit A) which had the following circuit parameters:

C = 0.97 microfarad

L = 0.58 microhenry*

R = 0.35 ohm

V_o = 2000 volts

A circuit can be underdamped, critically damped, or overdamped depending upon whether $R < 2\sqrt{\frac{L}{C}}$, $R = 2\sqrt{\frac{L}{C}}$, or $R > 2\sqrt{\frac{L}{C}}$. A critically damped circuit under our experimental conditions would have a resistance of 1.55 ohms. The basic circuit has a resistance of 0.35 ohm before insertion of the platinum bridgewire and is therefore underdamped. The circuit is initially underdamped for platinum wires 0.025, 0.050, 0.100, and 0.200 inch long but becomes overdamped with a 0.400 inch long wire. Results of the first test series are shown in Table I.

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*See Appendix A.

Table I. Initiation of PETN with Basic Circuit (Circuit A)

Shot No.	Wire Resistance (ohms)	Total Circuit Resistance (ohms)	Wire Length (inch)	Results
26	2.30	2.65	0.400	PETN initiated, did not grow to detonation
27	1.13	1.48	0.200	" " "
28	0.64	0.99	0.100	" " "
29	0.37	0.72	0.050	Detonation
30	0.28	0.63	0.025	"

The PETN was detonated with the 0.025 and 0.050 inch long wires. The three longer wires all gave definite current dwells. The duration of the current dwell increased as the length of the wire increased. Each of the three longer wires weakly initiated the PETN at the time of wire burst and accelerated the burning when the restrike occurred. However, detonation did not ensue. See Figure 2. The power, energy, and resistance values were computed as a function of time for the first current pulse into the 0.400 inch length wire. See Figure 3. Calculations based on the thermal properties of platinum show that approximately 85 millijoules of energy are required to bring the 0.400 inch wire length to the boiling point; 362 millijoules are required for complete vaporization. It can readily be seen from Figure 3 that insufficient energy is deposited in the wire to cause complete vaporization before the current dwell occurs. The resistance of the wire increases to 25 ohms in 0.2 microsecond. It remains at this level for 0.6 microsecond giving a current plateau characteristic of weak platinum wire explosions. The resistance then increases rapidly to over 300 ohms choking off the current, at which time the current dwell commences. The failure to effect detonation under the circuit conditions employed can be attributed to

1) the weak initial explosion of the wire because of insufficient energy deposition

2) the limitation and cessation of current flow because of the rapid resistance increase which in effect slows and then stops the input of electrical energy.

8. A second test series was conducted with 0.70 ohms extraneous resistance. Carbon resistors, placed between the capacitor and the 20 inch long coaxial transmission cable, were used to increase the resistance. This circuit (Circuit B) is underdamped initially with the 0.025, 0.050 and 0.100 inch long wires, and is overdamped with the 0.200 and 0.400 inch long wires. Test results are shown in Table 2.

Table 2. Initiation of PETN with 0.70 ohm Extraneous Resistance in Circuit (Circuit B)

Shot No.	Wire Resistance (ohms)	Total Circuit Resistance (ohms)	Wire Length (inch)	Result
31	2.36	3.06	0.400	PETN initiated, did not grow to detonation
32	1.15	1.85	0.200	" " " "
33	0.66	1.36	0.100	" " " "
34	0.42	1.12	0.050	" " " "
35	0.42	1.12	0.050	" " " "
36	0.25	0.95	0.025	Detonation
37	0.29	0.99	0.025	" "

Definite dwells again occurred with the 0.400, 0.200, and 0.100 inch wire lengths. The 0.050 inch long wire initiated a vigorous burning, but no detonation developed. Figure 4 illustrates the cavity that was burned into the PETN by the 0.050 inch long wire. Detonation developed only with the 0.025 inch length wire. See Figure 5. An examination of the current, voltage, power, energy, and resistance curves for the 0.025 inch long wire (Shot No. 37) shows a burst time of 0.26 microsecond with peak resistance and power occurring almost simultaneously. See Figure 6. The resistance of the wire increases rapidly, overdamping the circuit in less than 0.2 microsecond. At the time of burst the resistance is roughly twenty times the original resistance. Arc formation commences almost immediately after the wire burst with the resistance dropping to 0.25 ohm. This permits the current to execute an undamped half sine wave oscillation before cessation of the current flow, probably due to break-up of the test fixture. The detonation wave in the PETN meets the containing steel ring 2.5 microseconds after the

wire burst, at which time the resistance rapidly increases. Energy deposition is extremely slow for the first 0.2 microsecond, rapid during the voltage spike, followed by a steady rate until the test fixture is blown apart. At the time detonation commences in the PETN, (roughly 1.0 microsecond after the time of burst) 350 millijoules or 18% of the energy stored in the capacitor has been deposited in the wire.

9. A third test series was conducted with the extraneous circuit resistance increased to 2.45 ohms. This circuit (Circuit C) is overdamped without the bridgewires. Results of the third test series are shown in Table 3.

Table 3. Initiation of PETN with 2.45 ohms Extraneous Resistance in Circuit (Circuit C)

Shot No.	Wire Resistance (ohms)	Total Circuit Resistance (ohms)	Wire Length (inch)	Result
38	2.33	4.78	0.400	PETN initiated, did not grow to detonation
39	1.15	3.60	0.200	" " " "
40	0.67	3.12	0.100	" " " "
41	0.34	2.79	0.050	" " " "
42	0.29	2.74	0.025	" " " "

Definite dwells were again observed with the 0.400, 0.200, and 0.100 inch wires. The 0.050 and 0.025 inch long wires both initiated vigorous burning. No detonations occurred with any of the wires. An examination was made of the current, voltage, power, energy and resistance curves of the 0.025 inch length (Shot No. 42) to compare with the same size wire in Circuit B. See Figure 7. The burst time of the wire is 0.26 microsecond, the same as in Circuit B. The resistance of the wire increases rapidly to roughly about thirty-seven times the original resistance. Almost double that in Circuit B. The interval between the wire burst and arc formation is longer than for Circuit B. There is a marked reduction in peak power with 560,000 watts observed compared to 1,300,000 watts with Circuit B. Energy deposition is at a slower rate than in Circuit B with 180 millijoules deposited 1.0 microsecond after the burst time. The electrical processes are uninterrupted since detonation does not occur. Once the current reaches its maximum value, it decays

exponentially with a time constant equal to the RC value of the circuit.

DISCUSSION

10. The circuit before insertion of the wire can be underdamped, critically damped, or overdamped. A highly underdamped circuit will have a theoretical current maximum of

$$i_{max} = \sqrt{\frac{C}{L}}\, V_o = 2{,}590 \text{ amperes.}$$

The current waveforms for each of the three test circuits with a shorting bar in place of the wire are shown in Figure 8. Each increase in extraneous circuit resistance lowers the possible i_{max} in the circuit. Di Persio(2) has previously shown that there is a critical value of i_{max} depending upon the experimental conditions below which detonations will not occur. An analysis of the test shots reveals the same type of ordering with $i \doteq 428$ amperes (8.5×10^7 amps/cm^2) as the critical current with the experimental parameters employed. See Table 4. If the circuit is greatly overdamped and the current limited to less than 428 amperes then there will be no possibility of effecting detonation. The i_{max} ordering gives a good correlation with the probability of detonation for a specific wire size and set of circuit parameters. However, the value of i_{max} shows no dependency on time. While the critical value of i_{max} is good for a specific set of conditions, it cannot be assumed to apply if the time of occurrence of i_{max} was displaced so as to occur earlier or later. A critical power input should be one of the more important considerations.

11. The circuit even if initially underdamped, rapidly becomes overdamped with the 1 mil diameter platinum wires as can be seen from the resistance curves in Figures 6 and 7. This indicates that a wire material with a low resistance and coefficient of resistivity might be used to increase the current density in the wire. However, the energy going into joule heating of the wire at any instant will depend upon the ratio of the wire resistance to that of the entire circuit. This indicates that extraneous circuit resistance should be kept to an absolute minimum in order to keep the wire resistance/circuit resistance ratio high.

12. The addition of extraneous resistance to the circuit is expected to increase the burst time and reduce the current at the time of explosion (burst current) in the wire. As can be seen from Table 4, a lowering of the burst current is observed as the extraneous resistance is increased. However,

TABLE 4. Effect of Current on Detonation of PETN

Shot No.	Wire Length (inch)	Circuit*	Current at time of wire explosion (amperes)	Current density at time of wire explosion (amperes/cm2)	Result
37	0.025	B	503	9.9×10^7	Detonation
30	0.025	A	490	9.7×10^7	"
29	0.050	A	462	9.1×10^7	"
36	0.025	B	435	8.6×10^7	"
35	0.050	B	420	8.3×10^7	Deflagration
34	0.050	B	406	8.0×10^7	"
33	0.100	B	322	6.4×10^7	"
28	0.100	A	294	5.8×10^7	"
42	0.025	C	276	5.4×10^7	"
41	0.050	C	263	5.2×10^7	"
27	0.200	A	252	5.0×10^7	"
32	0.200	B	224	4.4×10^7	"
40	0.100	C	218	4.3×10^7	"
26	0.400	A	200	4.0×10^7	"
39	0.200	C	190	3.8×10^7	"
31	0.400	B	180	3.6×10^7	"
38	0.400	C	163	3.2×10^7	"

Circuit A - 0.35 ohm
Circuit B - 0.70 ohm
Circuit C - 2.45 ohms

the burst time for a specific length wire stays almost constant for each of the three test circuits. It was thought that the constant burst times might be attributed to the surrounding explosive, but wires not in contact with explosive exhibited the same burst time constancy in the three test circuits.

13. Some of the differences noted in the 0.025 inch length wire between circuit B and circuit C can be attributed to the so-called "anomalous effect". This effect was first reported by Kvartskhava et al[3] and later investigated by Tucker and Neilson.[4] They found that the burst time of the wire does not depend upon the energy delivered to the wire alone, but also on the value and duration of the current. The higher the current density at the time of the wire explosion, the greater the amount of energy deposited in the wire. At the time of burst, 33.8 millijoules have been deposited in the wire in circuit B and 19.2 millijoules in the wire in circuit C. Also, the resistance of the wire is not a unique function of the energy deposited in the wire, but depends upon the rate of energy deposition. Slower energy deposition results in a higher resistance. See Figures 6 and 7. Reithel and Blackburn[5] have proposed that inertial confinement of the wire may account for the resistance anomaly. They believe that when the current density is increased, the expansion of the wire is hindered in such a way that the electrical resistivity of the wire approximates that of a liquid long after sufficient energy for vaporization has been deposited in the wire.

14. According to RLC circuit theory, if the capacitance and inductance are held constant, the value of resistance that will most rapidly dissipate the energy stored on the capacitor is $R = 2\sqrt{\frac{L}{C}}$ (critically damped circuit). The resistance of the wire increases rapidly up to the time of wire burst and the circuit resistance can equal $2\sqrt{\frac{L}{C}}$ for only a brief instant during the current rise. After the wire burst, the sum of the arc resistance and the extraneous circuit resistance may again equal $2\sqrt{\frac{L}{C}}$ for a longer period. The $R = 2\sqrt{\frac{L}{C}}$ relationship does not appear to be of much use when applied to exploding bridge-wire circuits. The experimental results indicate that the initial energy deposited in the wire before burst is much more important than decreasing the discharge time of the capacitor.

CONCLUSIONS

A. The results show the importance of keeping extraneous circuit resistance to an absolute minimum.

B. Each increase in extraneous circuit resistance will lower the i_{max} in the wire before burst, which in turn results in a lower energy deposition into the wire.

C. The probability of effecting detonation is directly related to the current density in the wire for specific circuit parameters.

D. During the capacitor discharge the resistance of relatively long wires increases very rapidly limiting the current density in the wire.

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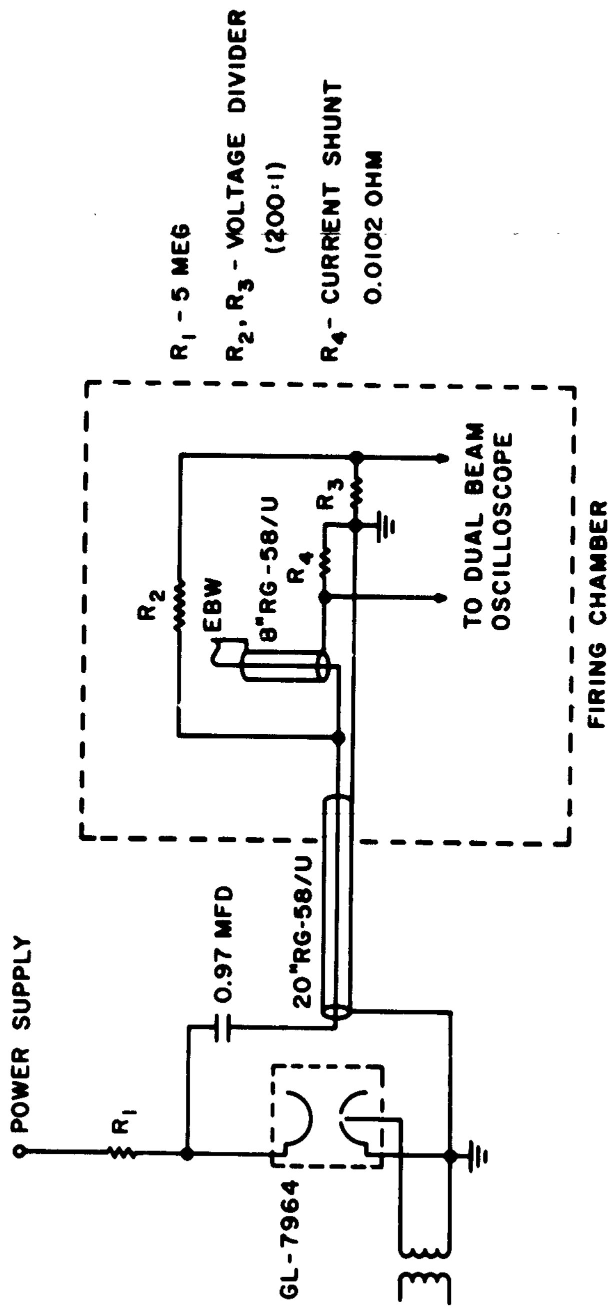

FIG. 1 FIRING CIRCUIT

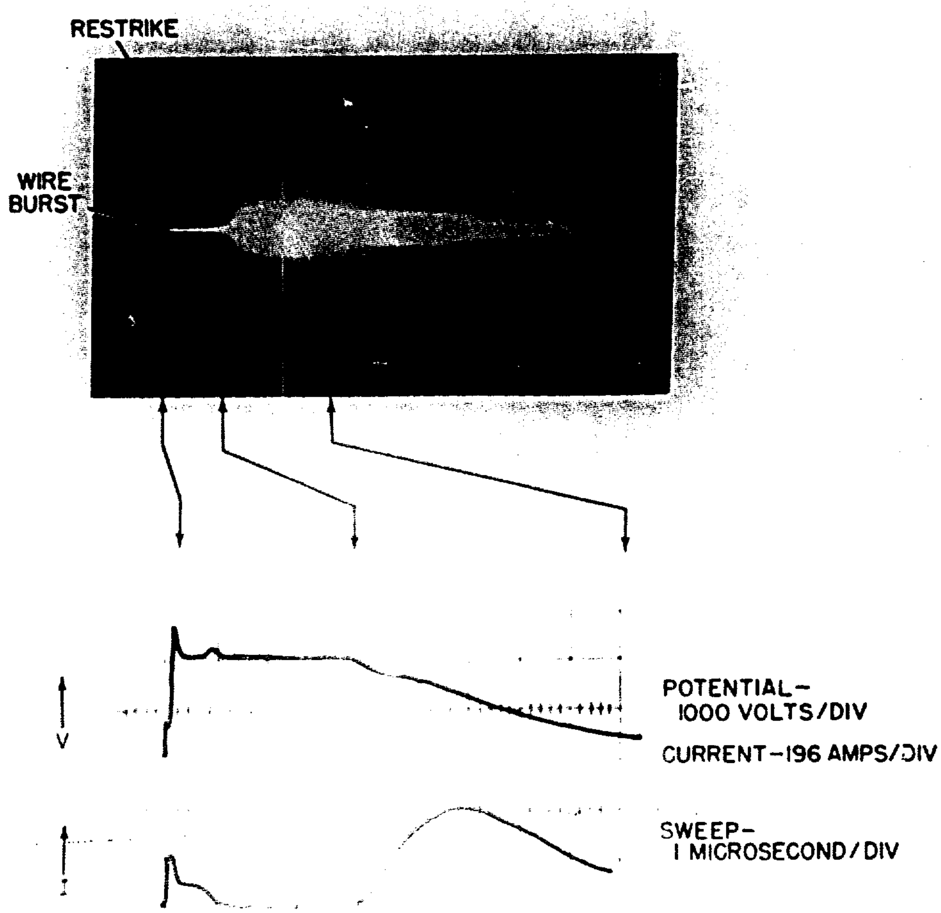

FIG 2 SMEAR CAMERA [illegible] RAM FOR TEST SHOT NO.26

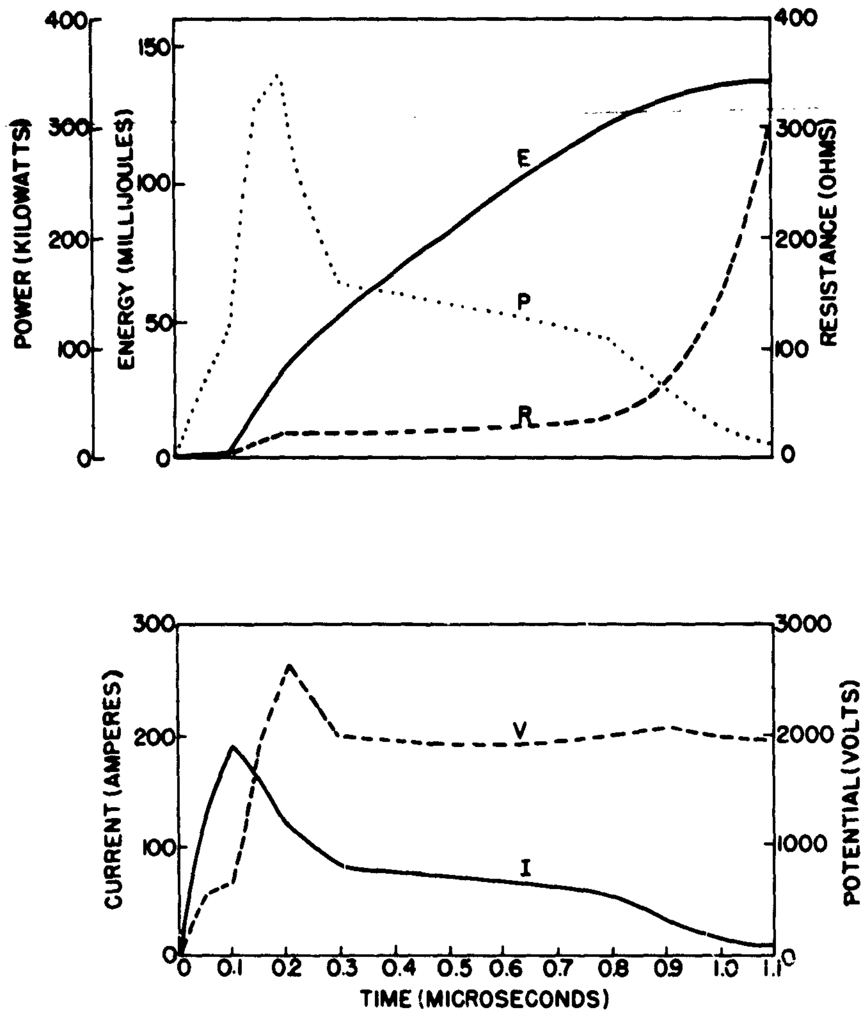

FIG 3. CURRENT, VOLTAGE, POWER, ENERGY AND RESISTANCE CURVES FOR TEST SHOT NO. 26

FIG. 4 TEST FIXTURES SHOWING PARTIAL BURNING OF PETN

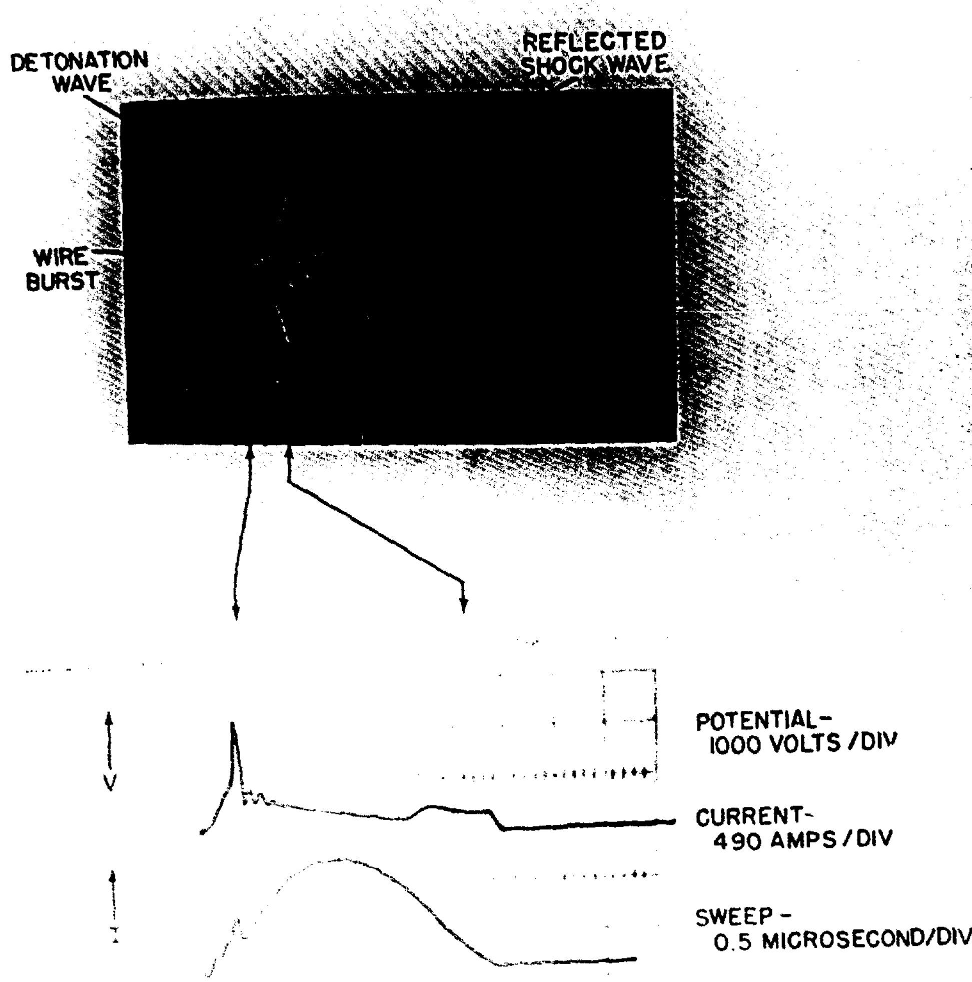

FIG 5 SMEAR CAMERA RECORD AND OSCILLOGRAM FOR TEST SHOT NO 37

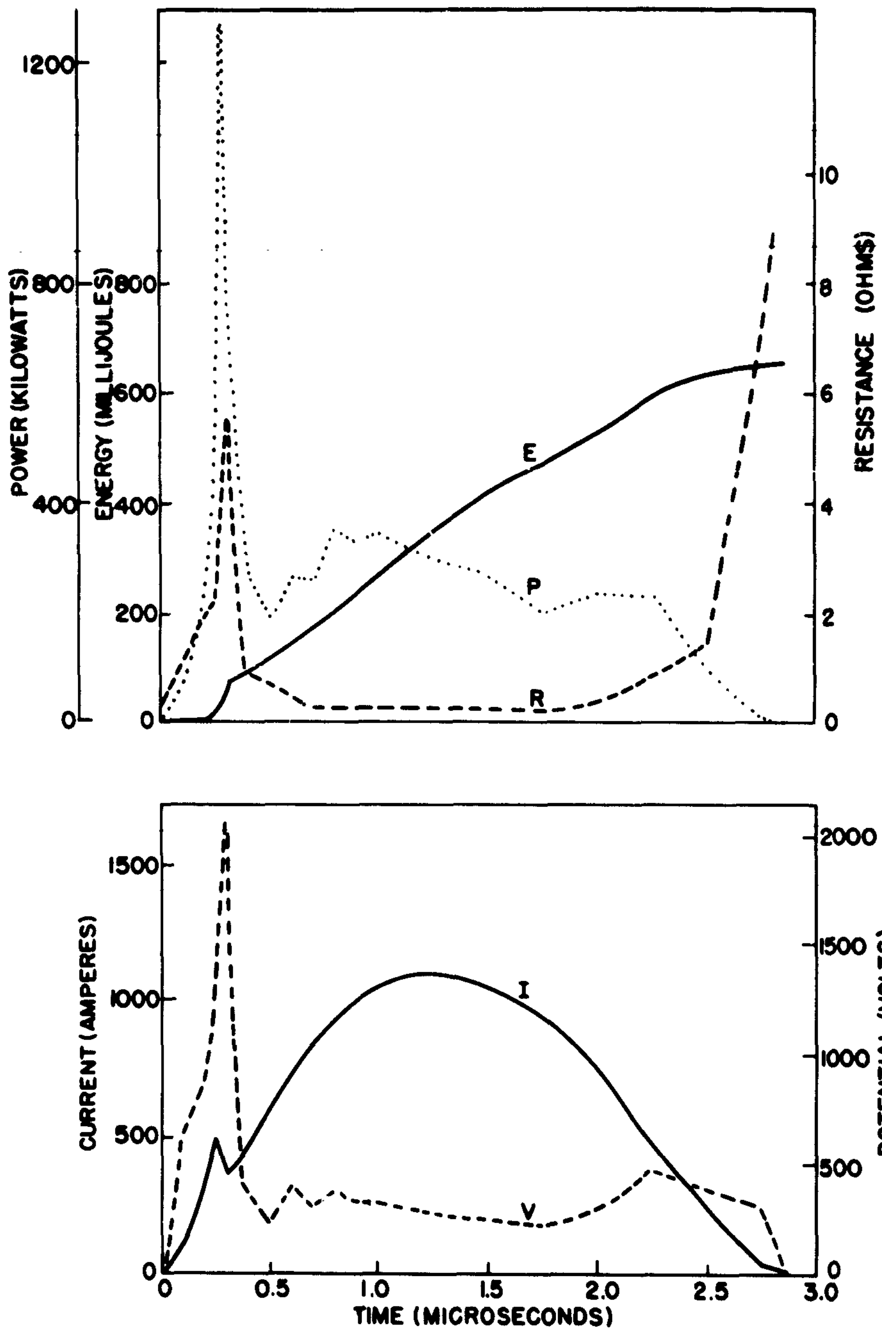

FIG 6. CURRENT, VOLTAGE, POWER, ENERGY AND RESISTANCE CURVES FOR TEST SHOT NO.37

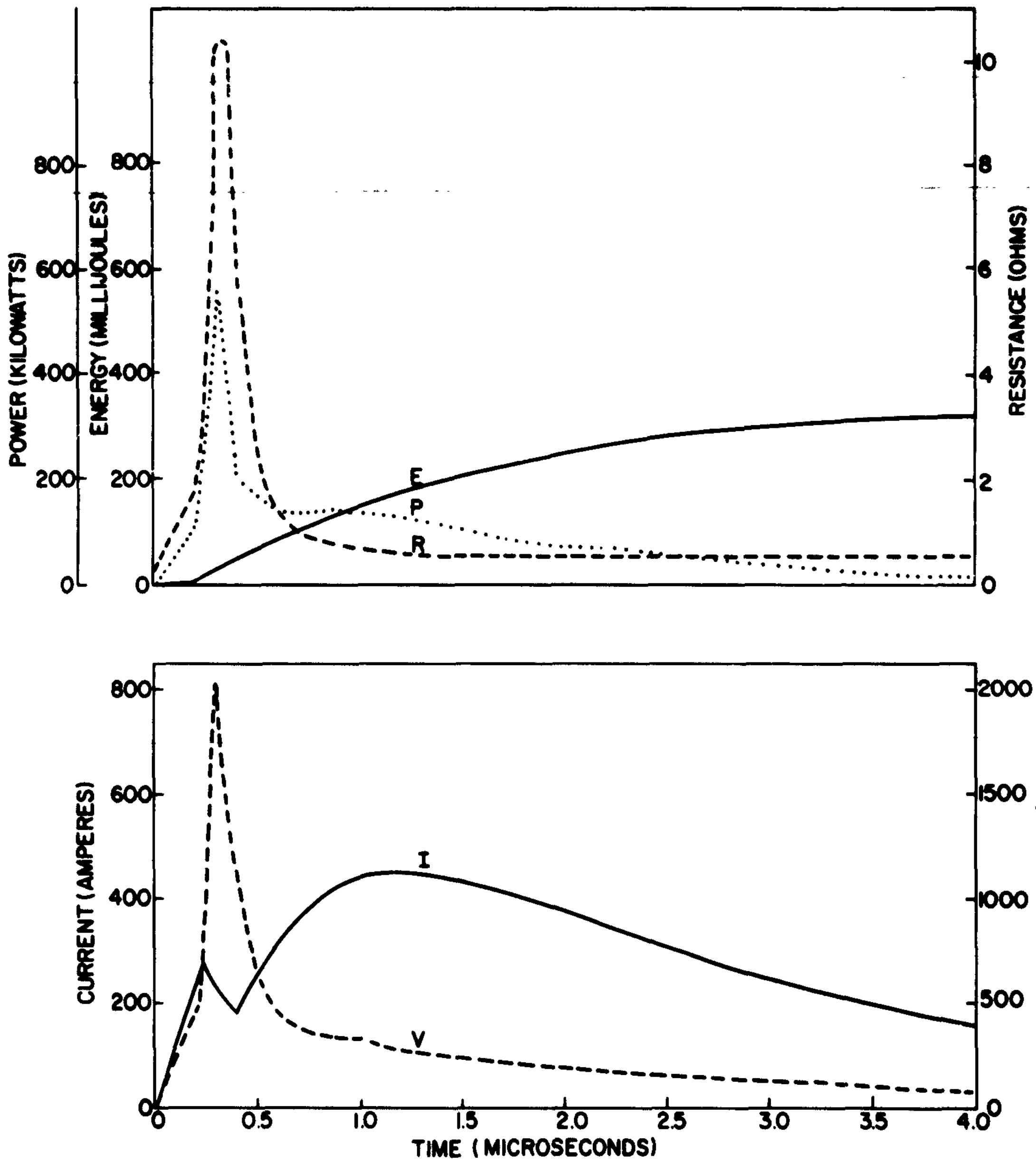

FIG. 7 CURRENT, VOLTAGE, POWER, ENERGY, AND RESISTANCE CURVES FOR TEST SHOT NO.42

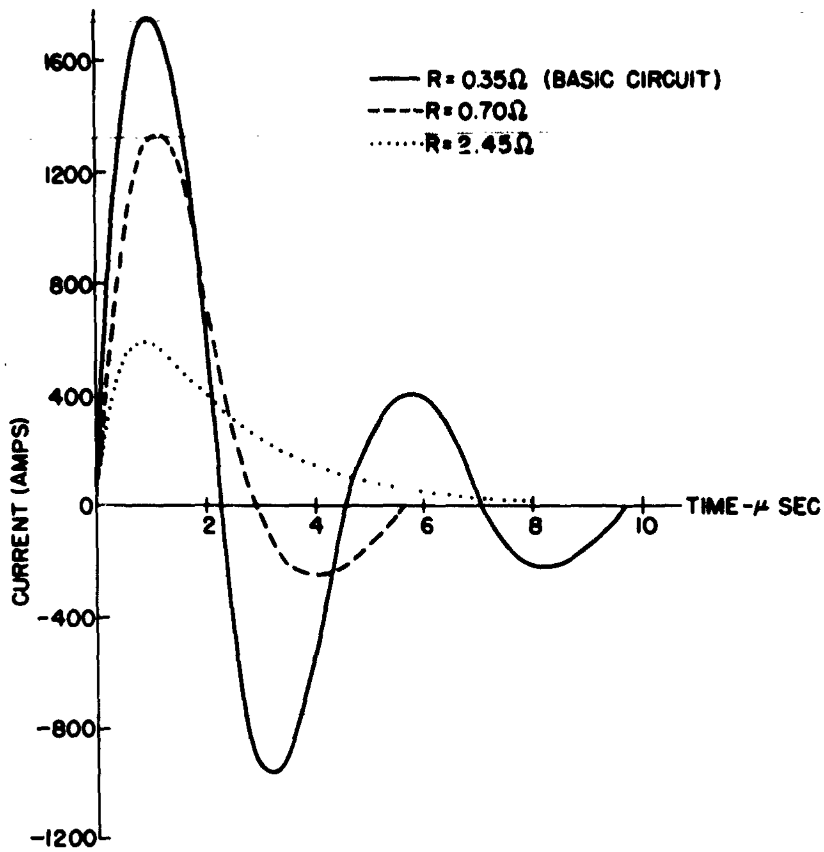

FIG.8 EFFECT OF CIRCUIT RESISTANCE ON CURRENT WAVEFORM

APPENDIX A

When the circuit inductance was determined by measuring the initial current slope from an oscillogram taken with a dead short replacing the bridgewire by means of

$$L = V_o / \left(\frac{di}{dt} \right)_{t \to 0} \tag{1}$$

where L = circuit inductance, V_o = initial capacitor voltage, and di/dt = initial current slope a value of 0.85 microhenry was obtained. This method was employed because the original circuit contained a thyratron as the switching element which gives only a half sine wave pulse and then shuts off preventing the use of an oscillation frequency method.

When the circuit inductance was determined by the simple oscillation frequency relationship for an underdamped circuit

$$L = \frac{T^2}{4 \pi^2 C} \tag{2}$$

where T = period of oscillation, and C = capacitance, a value of of 0.61 microhenry was obtained, roughtly 28% lower than the value obtained by the slope method.

If the circuit parameters are determined by use of the following relationships

$$\delta = \log e \frac{I_1}{I_2} \tag{3}$$

$$L = \frac{T^2}{C(4_\pi{}^2 + \delta^2)} \tag{4}$$

$$R = \frac{2L\delta}{T} \tag{5}$$

where δ = logarithmic decrement of the current, I_1 = first current maximum, I_2 = second current maximum, and R = effective circuit resistance;

values of 0.58 microhenry for the circuit inductance and 0.35 ohm for the circuit resistance are obtained. The resistance value agrees exactly with the value derived previously from a single half sine wave measurement indicating that the resistance figure is reasonably valid. Bennett[6] in a study of transient conditions at switch-on has shown that a coaxial current shunt will underestimate the original current slope by 10% or more.

This means the observed $\frac{di}{dt}_{t \to 0}$ will be less than predicted by RLC circuit theory and hence will give an overestimate of L when used in relation (1). For this reason it is believed that the lower figure obtained by the oscillation frequency method represents a truer value of the circuit inductance.

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			BIBLIOGRAPHIC (SUPPL., VOL., ETC.)	Part 2	PRTB2

SUBJECT ANALYSIS OF REPORT

DESCRIPTORS	CODES	DESCRIPTORS	CODES	DESCRIPTORS	CODES
Explosives	EXPL	Electric	ELEC		
Effects	EFFE	Charge	CHAR		
Circuit	CIRC	Current	CURR		
Resistance	REST	Density	DENS		
Initiation	INIT	Input	INPU		
Exploding	EXPI	Detonation	DETO		
Wires	WIRE	Penta	PENA		
Bridge	BRID	Erythritol	ERYT		
Length	LONG	Tetra	TERA		
Platinum	PLAT	Nitrate	NITT		
Capacitor	CAPA				
High energy	HIGE				

PRNC-NOL-5070/28 (5-62)

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 63-244)
INITIATION OF EXPLOSIVES BY EXPLODING WIRES (U), by Howard S. Leopold. 15 May 1963. 20p. illus., tables. BuWeps task RUME-4E000/212-1/F008-10-04.

UNCLASSIFIED

The effects of circuit resistance and bridgewire length on the initiation of PETN by exploding 1 mil diameter platinum wires were investigated. A one microfarad capacitor charged to 2000 volts was used as the energy source. Increasing circuit resistance reduces the current density and the energy input to the wire lowering the probability of producing detonation in PETN. The importance of keeping the extraneous circuit resistance to an absolute minimum is shown.

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2. Explosives - Initiation
3. Wires, Exploding

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III. Project
IV. Title: Effect of circuit...

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